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Review of the impact of urban block form on thermal performance, solar access and ventilation

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ABSTRACT

Cities use a big amount of energy resources and account for over 70% of global carbon emissions. Form and position of urban blocks not only influence the micro-climate but also the energy performance of each block; so, considering the building without studying the effect of its surroundings is senseless.

This paper provides a review of research on the impact of urban block form on the environmental performance of buildings and their direct environment. For this purpose, all papers are categorised in three main groups:

- Thermal behaviour inside and outside the building.
- Solar access inside and outside the building.
- Indoor and outdoor natural ventilation.

A discussion of these studies reflects the impact of urban block form parameters on the energy performance of the building and reviews existing methods and techniques to predict thermal behaviour, solar access and ventilation on a neighbourhood scale. This study is useful for planners and architects who are responsible for decision-making during the design phase.

Contents

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1. Introduction

After the industrial revolution, the use of fossil fuels for providing a comfortable temperature has grown. Today about 50% of the world population is living in a city and this amount will reach up to 80% by 2030 (Fig. 1). Cities use a big amount of energy resources and account for over 70% of global carbon emissions [1–5].

Architects [7] and urban planners [8] have concentrated on the relation between energy consumption and neighbourhood form since the 19th century. The relationship between buildings and their surroundings is an interdisciplinary challenge for architects, urban engineers and meteorologists [9]. Originally, meteorologist were interested in the effect of urbanisation on climate change, urban planners studied the impact of urban morphology on the energy use of and thermal comfort in buildings and urban environments [10–14] and the architects considered energy and comfort mostly on the building scale [14–16].

From the 1960s, planners and architects understood that it was not enough to solely focus on individual buildings but that it is important to broaden the analysis to groups of buildings or urban blocks [17]. The thermal behaviour of buildings is altered when buildings are laid in a cluster [18]. One of the aspects important in the planning of urban blocks is the impact of urban form on energy use. In the meantime, there have been several studies focussing on the neighbourhood [19–21].

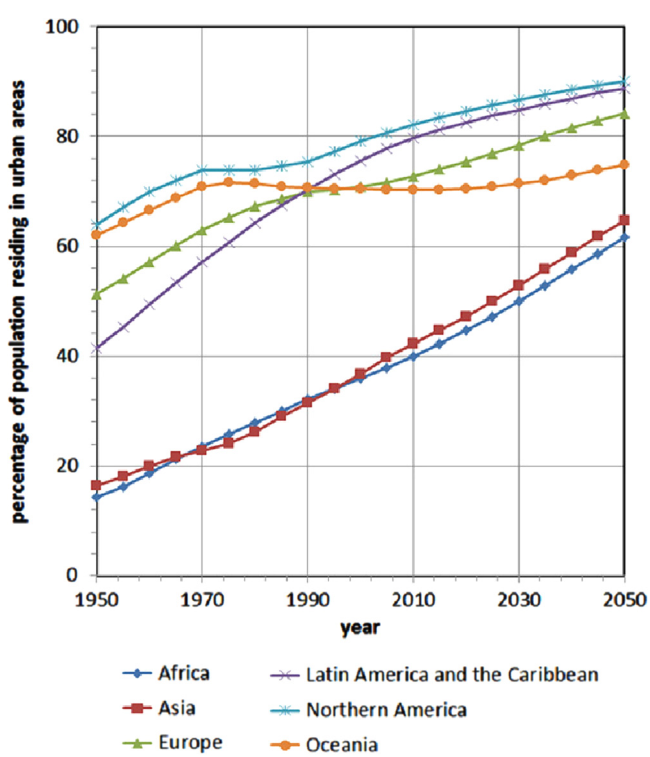

Fig. 1. Percentage of world population living in cities 1950–2050 [6].

The energy performance of buildings, as Baker and Steemers [22] argue, depends on five factors: climate, urban geometry, building design, systems efficiency, occupant behaviour. The variation in energy consumption caused by building design equals a factor of 2.5; by systems efficiency a factor of 2 and by occupant behaviour also a factor of 2 (Fig. 2). The effect of the urban context was not quantified by them. Urban geometry affects the amount of solar radiation on the building envelope and also the microclimate and airflow pattern around buildings. The impact variation of urban form on the energy performance of buildings is therefore complex [22,23]. As Givoni [24] mentioned, the regional 'synoptic' climate is the local microclimate that results from the neighbourhood where the building is located.

According to Yamaguchi et al., the effective design and planning of city neighbourhoods, of the distribution of buildings and of energy-consuming equipment can achieve a reduction of 60–90% of the current CO_2 emissions by the middle of the 21st century [25]. The position of neighbouring units and building morphology influence directly the accessibility to solar radiation from both the indoor and outdoor environment [26–28]. Orientation and neighbourhood patterns not only affect solar access but also airflow patterns and wind speed. Furthermore, the placements of buildings within the site and land use patterns strongly influence the outdoor air and radiant temperature of the microclimate created by city blocks [29–32].

This paper will review the literature on the effect of urban blocks on energy performance and try to give an overview of studies that focused on urban blocks instead of a single building. The environmental impact of urban block form will be investigated from three perspectives: the thermal impact of urban blocks, the solar access in urban blocks and the effect of building geometry on ventilation. Each perspective is categorised in two sections: first, parameters and second, techniques and methods.

2. Methodology

This study systematically reviews recent research on the effect of urban block form on thermal behaviour of buildings. The interrelationship between urban block form and climate has been the subject of many papers. Most publications can be categorised in three main groups. Studies that

1. Investigate the effect of urban block geometry on the thermal behaviour inside and outside the building [7,15,24].
2. Focus on issues of solar access inside and outside the building for passive heating and daylighting purposes [21,33–36].
3. Evaluate the effect of urban block form on indoor and outdoor ventilation [37,38].

This systematic research tries to categorise all studies in these groups but it should be underlined that some studies tend to overlap because some of the researchers studied multiple parameters simultaneously.

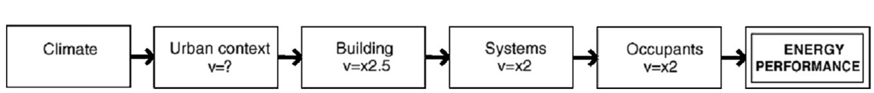

Fig. 2. The contribution of five factors in energy usage of buildings; according to Ratti et al. [25].

All papers in each category are investigated in two main sections. The first section deals with the geometry related parameters that affect heat losses, solar access and ventilation while the second is about the techniques and methods used by the researchers in order to study these parameters.

3. Thermal impact of urban blocks

The knowledge that now exists about the thermal impact of the neighbourhood can help increase the energy-efficiency of and thermal comfort in buildings through the application of passive heating, cooling, ventilation, and daylighting strategies [39].

Strømann-Andersen and Sattrup [40] found that the geometry of urban canyons has an impact on the total energy consumption of buildings in the range of up to 30% for offices and 19% for houses. This shows that the geometry of urban canyons is a key factor in the energy use of buildings.

The energy consumption in urban environments can be categorised into three main groups.

- **Operational energy** used for the heating and cooling of dwellings and for appliances used within them. This can be grouped into building-related operational energy and use-related operational energy.
- **Embodied energy** used for the manufacturing, distribution and deployment of materials used in the construction of dwellings and their associated infrastructure.
- **Transport energy** (both private and public) used for transport [41].

Concerning urban block form, embodied energy and operational energy have the biggest effect on energy consumption. There are some studies that compared the embodied energy of buildings to the operational energy [42–44]. Most of these researches indicated that over the lifetime of a building (typically 50 or 100 years), the share of operational energy is still dominant (80–90%) [45].

3.1. Effect of building geometry on operative energy performance

In the middle of the twentieth century, the moving away from urban blocks with inner green courtyards gave way to a space-consuming building layout in parallel blocks. This transformation was theoretically based on the Modern Movement [46]. Gropius [47] in 1930, a German architect and urban planner, looked into the question of a rational building layout that guaranteed daylighting and ventilation. He laid out three rules for parallel block layout, around four different variables: the number of storeys, the population density of each block, the site area and the incidence angle of sunlight at the bottom of the buildings in winter [48]. The Gropius rules are

- On a given site area and sunlight incidence, the number of inhabitants increases with the number of stories.
- On a given sunlight incidence and a given number of residents, the size of the required site decreases with the increasing number of stories.
- On a given site area and a given number of inhabitants, the sunlight incidence decreases with the increasing number of stories.

With these three rules Gropius argued that high-rise buildings, 10–12 stories, were better than 3-, 4-, or 5-storey buildings: better in terms of a higher population density which can be achieved at lower cost while preserving light, air and elbow-room. In particular, he argues that the amount of open space for each inhabitant (the open-space ratio) increases as the height of the blocks increases [46].

“What building forms make the best use of land?” [49] This question for planners and architects was addressed in the late 1960s at the Centre for Land Use and Built Form Studies in Cambridge by Leslie Martin, Lionel March, Michael Trace and others [50]. Answers to this question have a lot of influence on urban planning and architecture. To find the answer for this question first the optimum land-use should be defined, such as the relation between the ratio of built area to site area and the availability of daylight [51].

The shapes of the urban blocks studied by Martin and March (Fig. 3) were considered by the researchers who were interested in thermal impacts of urban form. The main question was if the thermal behaviour of these forms could also have a determining role in the use of them. For example, Steemers et al. [52] were interested in the relationship between the urban micro-climate and the form of the building. They used the forms from Martin & March and investigated the relationship between building density and energy consumption. They concluded that courtyard houses have the best response to climatic conditions in London.

The surface-to-volume ratio (S/V) is an indicator of the compactness of buildings and the urban context and can be used to evaluate the total heat loss [51]. The surface-to-volume ratio must be considered carefully. Minimisation of the surface-to-volume ratio leads to a decrease of heat losses during the cold season but may increase the energy consumption for artificial lighting because of minimising the facades exposed to solar rays [23].

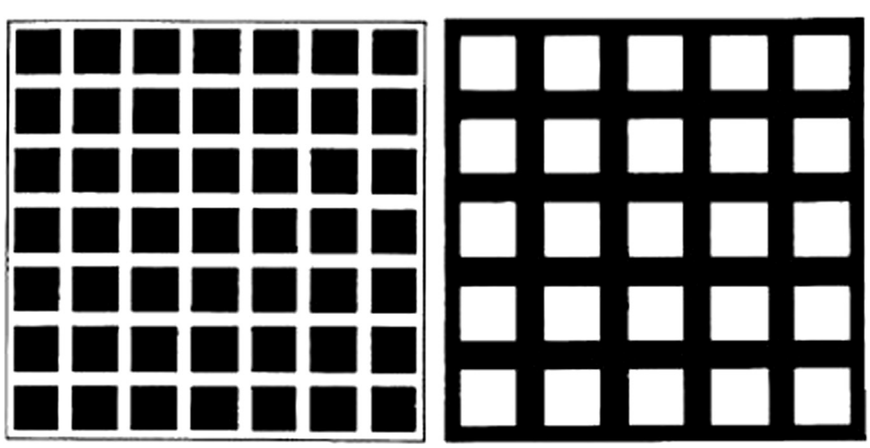

Fig. 3. Pavilions and courts (black represents buildings) with the same site coverage, building height and total floor space [51].

Under the same plot ratio (height/width ratio (H/W)), according to Ratti et al. [50], the forms that were created by March [49] are very simple and in practice non-existent. Consequently, Ratti and Raydan decided to study one valid urban context and to investigate the ratio of surface-to-volume, the concentration of shade, access to sunlight and views to the sky. They concluded that efficiency results of urban forms are based on the climate area in which they lay. The case study showed that the courtyard layout responded better to environmental factors (surface-to-volume ratio, shadow density, daylight distribution, and sky view factor) than pavilion-shaped types in a hot arid climatic area. They deduced that the courtyard type would not be an appropriate solution in a hot humid climate (tropical) and that building proportion has the main impact on the thermal behaviour of buildings as a result of which only a limited number of courtyard houses are thermally beneficial.

Taleghani et al. [29] showed the importance of surface-to-volume ratio in achieving thermal comfort and saving energy. They indicated that a single-family house with no open space is more energy-efficient than a courtyard, an atrium and a building with a sunspace in Rotterdam in the Netherlands (52°N).

When investigating the environmental effects of urban blocks on the outdoor environment (courtyards, streets and squares) the ratio of building height to street width is important. This ratio is defined by the vertical height to the horizontal width of the street [46]. Brown [53] defined directional space ratios (H1/W1, H2/W2, etc.) for court spaces to analyse the relation between directional H/W, incident solar radiation and wind patterns.

The ratio of passive to non-passive space is another indicator which is used for clarifying the influence of built form base on energy use. This ratio shows the impact of urban block form on building energy consumption. Gupta has assessed and compared three building archetypes during their construction as a function of their thermal behaviour in an arid climatic zone: the pavilion, street, and courtyard, as non-air-conditioned buildings [10,13].

Steadman [54,55] claimed that the one of the most important factors concerning the energy performance of the city structure is the ratio of passive to non-passive space. Ratti et al. [50] suggested six archetypal forms linked with several basic indicators, especially the ratio of passive to non-passive floor area. They concluded that there is almost 10% relationship between urban morphology and the annual energy consumption of non-domestic buildings [23].

Yang et al. [56] studied four parameters that influence the thermal environment around urban blocks during both summer and winter in Beijing's climate: block height, thermal mass, material conductivity and surface albedo. They concluded that block height is the most important, and surface albedo the least important factor.

3.2. *Effect of building geometry on embodied energy performance*

Besides the operational energy requirements of buildings, it is important to consider embodied energy. Embodied energy not only is the energy input required to mine, transport and manufacture building materials but also the energy used in the construction process. It can be helpful to determine design decisions on system or material selection [57].

Most research which investigated low energy buildings focused on operational energy. Research findings in some countries indicated that the operational energy often represents the largest component of life-cycle energy use [42].

There are some studies, though, which evaluated single houses or multi-storey buildings from a life-cycle perspective [58–61]. These studies showed that the significant part of the total energy use in a building is embodied energy. For example Junnila and Horvath [58] investigated the embodied energy of materials for high-rise buildings.

Concerning the urban field, there are other quantitative studies which investigated embodied energy in relation to urban density. An important example is the extensive analysis by Norman et al. [62]. They performed a comprehensive analysis of energy use in two distinct Toronto neighbourhoods. They evaluated daily transportation and household energy consumption between low- and high-density neighbourhoods regarding the impacts of embodied energy.

Their approach provided a holistic evaluation of all energy consumption across the two neighbourhoods, and showed how the low-density neighbourhood could be 2–2.5 times more energy-intensive (per capita) than the high-density neighbourhood, with the embodied energy of neighbourhood materials accounting for around 10% of the life-cycle energy use, transportation accounting for 20–30%, and building operations for 60–70%. Few, if any, other work provides their level of detail and scale. Importantly, their results suggest that the embodied energy is a significant portion of a neighbourhood's energy use, and should be granted more consideration in land use and transportation analyses.

There are only a few studies which investigated the impact of urban block form on embodied energy, so there is a need for analyses which focus on various components of urban blocks and utility infrastructure.

3.3. *Thermal analysis techniques and methods*

Several models and simulation techniques have been developed to study and describe the energy performance of buildings in relation to their surrounding micro-climate. However, most of these studies have been conducted by building designers who focused on buildings as individual blocks neglecting to the urban context in which the building is placed.

Most building simulation software is designed to concentrate on buildings and systems design. Most of these neglect the importance of the impact of the surrounding on the thermal behaviour of a building, as a result of which the effect of building block geometry on energy consumption still remains disputed.

Howard et al. in their guide on selecting building energy simulation programs, reviewed 33 software packages, 10 of which were developed to simulate energy consumption on the city scale estimating the effects of urban geometry [63].

In the late 1990s, researchers started to shift their focus from individual buildings to the neighbourhood and tried to simulate the impact of the environmental performance of this neighbourhood on buildings. Initial work used simplified energy modelling tools connected to Geographical Information System (GIS) software to improve energy conservation and increase the yield of solar thermal and photovoltaic panels on existing residential buildings [64–66].

There are three important methods which are used on an urban level to predict the energy performance of buildings:

- Energy and Environmental Prediction (EEP)
- Building Research Establishment Housing Model for Energy Studies (BREHOMES)
- Digital Elevation Models (DEM) and lighting and thermal (LT)

Although all three are concerned with predicting building energy consumption in urban areas, each one addresses the problem of data collection in different ways [64].

The energy and environmental prediction (EEP) model which is based on GIS techniques, developed at the Welsh School of

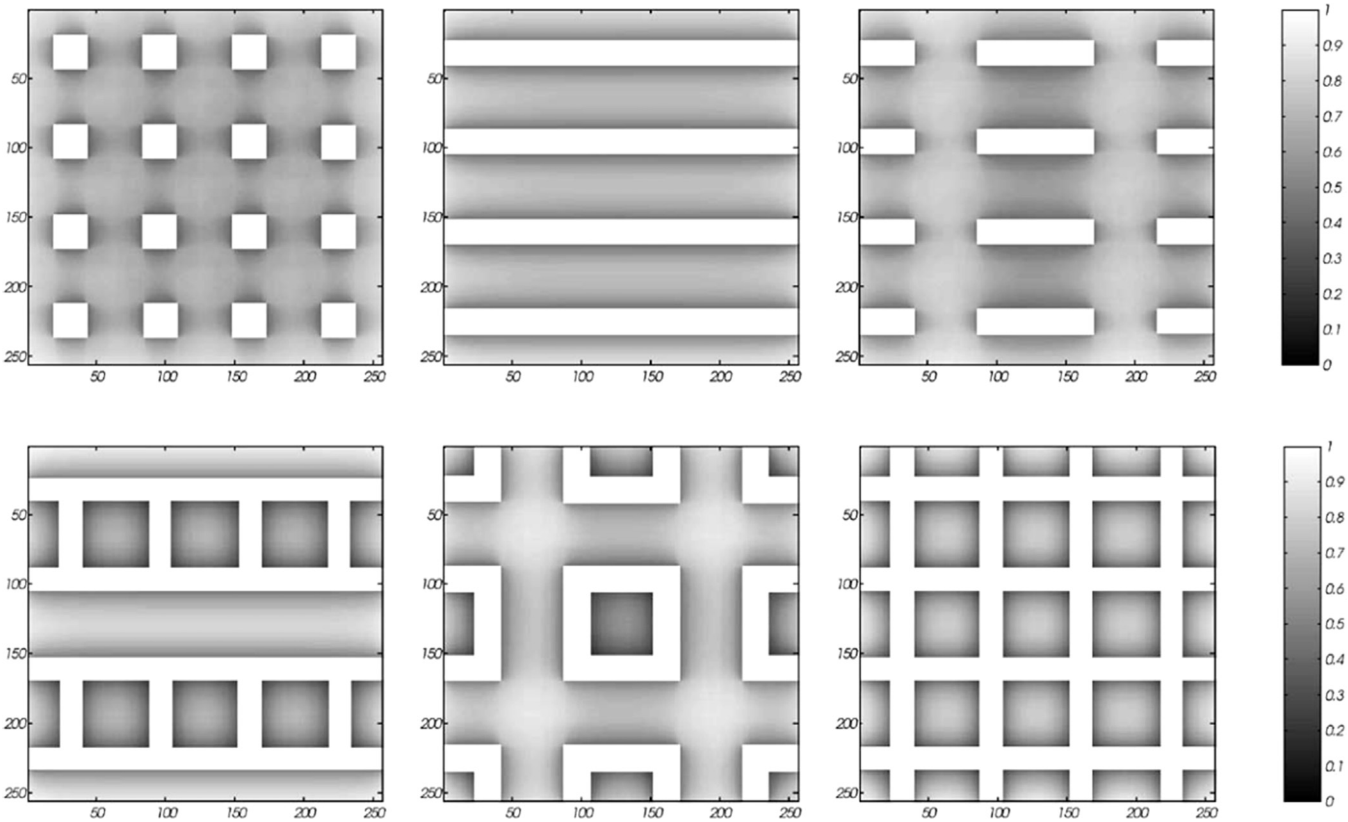

Fig. 4. DEMs of Generic urban forms, based on Martin and March and environmentally reviewed by Ratti, Raydan [51].

Architecture in Cardiff (1994), is used for domestic buildings. The model can predict the effects of future planning decisions from a whole city level down to a more local level. The user can identify 'hotspots' of energy use and emissions that can be targeted to make environmental improvements. Clustering is carried out on the basis of only four variables related to built form: heated ground floor area, total façade area, ratio of window to wall area and the area of the property [67].

The Building Research Establishment Housing Model for Energy Studies (BREHOMES) calculates the energy consumption of houses using the annual energy use in the UK housing stock. It is therefore inappropriate for considering individual dwellings [64].

Ratti et al. [50] studied Martin's and March's forms in hot and dry climates by using a technique for the analysis of the urban environment, based on image processing (DEM)(Fig. 4). They demonstrated the effect using a calculation that compares the DEM with the LT method developed by Baker and Steemers [22,68]. LT-Urban predicts building energy consumption by modifying the effects of *lighting and thermal* (LT) [68,69], meanwhile parameters which describe the building fabric (for example, orientation of facades and angles of obstruction of the sky) are derived using DEMs (Digital Elevation Models) [64].

4. Solar access in urban block

"The sun is fundamental to all life. It is the source of our vision, warmth, energy, and the rhythm of our lives. Its movements inform our perception of time and space and our scale in the universe. Guaranteed access to the sun is, thus, essential to energy conservation and to the quality of our lives" [33].

Solar radiation is an important constituent of climate and is highly important for human thermal comfort, indoors and outdoors [14,33,70,71]. In ancient architecture, one of the most important factors to generate the city was access to solar rays [30,72,73]. There are multiple evidences in vernacular architecture all around the world. The purpose of designing with sun is to achieve that sunrays would illuminate the inside of buildings and sidewalks for a desirable period in the cold days. Ignoring the solar rights of buildings and open spaces may cause discomfort [74].

Solar energy can be used not only passively for heating and daylighting but also actively for electricity and domestic hot water production [75]. Several parameters affect solar access, which include building orientation and shape, density within a site and site layout [28,76]. Therefore, architects and planners should consider both building form and the surroundings in the early stages of the planning process (Fig. 5).

4.1. *Effect of building form on solar access*

Neighbourhood solar design relies on three main factors: density of development, Orientation of the building and street layout. Key parameters such as building shapes, their density within a site, and the site layout can be optimised to achieve net zero overall energy consumption [60].

The building and its neighbourhood morphology have the largest effect on the access of solar energy [20,24,61]. There have been several studies that focused on the impact of urban block form on solar access [20,25,27,52,61–66]. Littlefair [76,78], for example, tried to find the link between urban geometry and individual building's solar access. Moreover, Okeil [39] developed a generic built form pattern named the residential solar block (RSB). After comparing the direct solar radiation distribution on urban surfaces, among which the RSB, the slab and the pavilion-court, he proposed the RSB as an interesting form for increasing

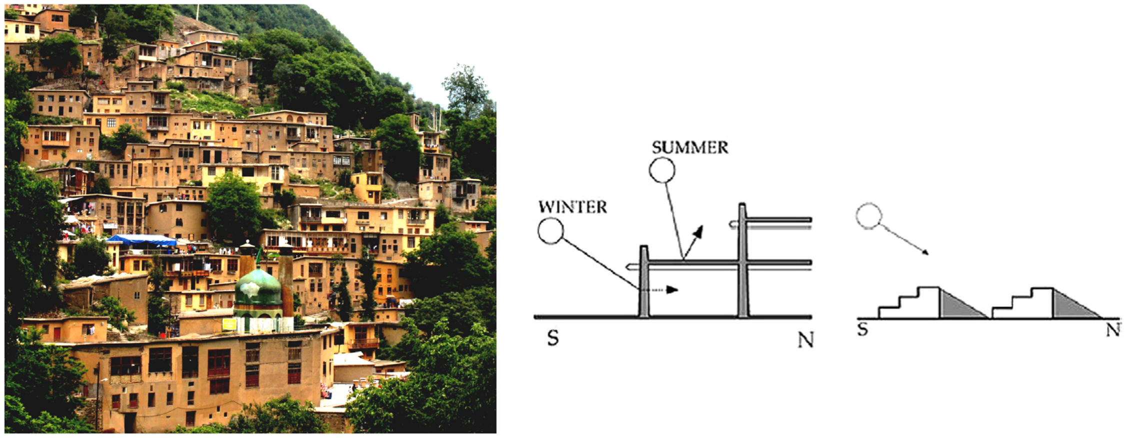

Fig. 5. Left: Masooleh, Iran. Right: Acoma Pueblo: thick masonry walls and roof terraces respond well to seasonal migrations of the Sun [78].

the amount of solar rays on roofs and facades and on the ground in the cities at a latitude of 25° [79,80]. Kämpf and Robinson [81] focused on the design of new urban forms and applied a multi-objective optimisation algorithm to minimise the energy demand of buildings in an urban area and to maximise the incident solar radiation whilst accounting for thermal losses. Their method can also be applied to existing forms.

There are several factors related to building form and neighbourhood that affect solar access

- urban density,
- orientation of the building's façade,
- building outlines and streets (ratio of building heights to the street widths).

Urban design parameters (street width and urban density) and building design parameters (Orientation of the building's façade and building outlines design) have important effects on solar access to the urban canyon and into buildings. Being able to understand the solar potential is important for architects and urban planners. Urban density impacts the solar potential of buildings by increasing the area shaded by neighbouring buildings. Orientation of the building's façade is another important factor which determines solar penetration into buildings. The design of the outlines of a building and of streets is a key issue in bioclimatic urban design. The facade can be seen as the interface between the architectural and urban scale as it consists of the shared surfaces between both. All of these factors should be investigated to improve solar access in urban blocks.

4.1.1. *Urban density*

One of the most important urban parameters which affect solar access is urban density. Urban density impacts the solar potential of buildings by increasing shading by neighbouring buildings [82]. Cheng et al. [35] conducted a parametric study to address the best urban configuration from a solar point of view. They examined the relationships between built form, density and solar potential with reference to three design criteria: (1) openness at ground level, which is highly related to pedestrian comfort; (2) daylight availability on the building façade, which indicates the daylight performance in buildings and (3) PV potential on the building envelope, which represents a significant area for the application of PV cells. The findings of this study provide some helpful insights for the planning of high density solar cities. Hachem [27,75] mentioned some points which should be addressed: how to design the urban morphology to get the maximum solar access under a given density, how to find the best place for buildings to avoid shading, and how to benefit from street shape, or to include street shape as a design parameter in order to enhance the overall energy performance of a neighbourhood.

4.1.2. *Orientation of the building's facade*

The orientation of building's façades is another important factor in the solar study of urban blocks. Ghosh and Vale [83] calculated the roof area suitable for solar thermal and solar PV. They concluded that on a local scale, roof form and orientation of buildings have a considerable impact on generating solar energy. Kanters and Horvat [84] studied geometrical forms of urban blocks and their solar potential. They studied four urban blocks of the city of Lund in southern Sweden and found that the impact of the morphology on the potential of solar energy was significant. They concluded that access to sunlight decreased by 10–75% if the urban blocks were surrounded by other buildings.

4.1.3. *Building outlines and streets*

A large number of solar recommendations related to the ratio of building height to the street width have been established [48,85]. The building outline is the virtual volume that buildings must not exceed. This ratio is defined by the vertical height to the horizontal width [46,48]. As Meir et al. [86] mentioned, in terms of shading, a greater H/W ratio along a given axis will reduce direct exposure of horizontal and vertical surfaces to sun. Furthermore, van Esch et al. [14] discussed the effects of urban design parameters (street width and orientation) and building design parameters (roof shape and building envelope design) on solar access to the urban canyon, and on the viability of passive solar heating strategies in residential buildings. The conclusion showed that street width has considerable influence on the total global radiation but street orientation hardly has effect on radiation. Moreover, Gupta [18] compared the access of solar energy of some forms according to parameters like building height, street width and orientation in hot and dry climates. Gupta completed his studies by investigating the relationship between sunlight per square metre facade and the energy consumption of a building for heating and cooling.

4.2. *Solar analysis techniques and methods*

There are some methods and tools to calculate the daylighting and solar access of buildings, like

- Daylight Factor (DF),
- shadow maps,
- irradiation maps,

- image-processing techniques and
- solar envelope.

A simplified method is based on the calculation of *the Daylight Factor* (DF) [87], defined as the ratio of the daylight illuminance on a plane to the illuminance on a horizontal plane in a free outdoor environment. The DF provides information about which parts of the indoor environment are bright or dark. The average daylight factor DF_{av} is an indicator that shows the visual adequacy of daylighting in a space as a whole rather than at any particular point [88].

Compagnon [89] proposed a method to quantify the potential of facades and roofs located in urban areas for active and passive solar heating, photovoltaic electricity production and day lighting. As a case study he compared different building layouts with constant density in Fribourg (Switzerland). His method can be used in the early stages of designing but still need to be refined, especially regarding irradiation and illuminance and needs to be further validated.

Redweik et al. [90] explained a method for the evaluation of the solar potential of envelope surfaces (roofs and facades) in an urban block with a spatial resolution of 1 m. This method calculates hourly (façade) shadow maps for the estimation of the direct solar radiation and (façade) sky view factor maps for the estimation of the diffuse radiation. This methodology can be used for a preliminary analysis of the solar potential on the city or neighbourhood level. The method was implemented using a solar radiation model based on climatic observations and applied to a case study area on the Campus of the University of Lisbon. The results confirmed that the annual irradiation on vertical facades is lower than on more favourable surfaces like roofs. However, due to their very large areas, the solar potential of facades is relevant for the overall solar potential of a building and/or an urban area. These results are useful for the development of solar dissemination policies and urban planning.

Mardaljevic and Rylatt [91], on the other hand, used sophisticated modelling to produce accurate irradiation maps for building surfaces in any urban context, presenting it as a detailed analysis technique for planners and designers. Related, Gadsden et al. presented a tool that assesses the potential solar energy fraction in domestic neighbourhoods using a GIS interface.

Ratti et al. [50] applied *image-processing techniques* to assess aspects of environmental performance and demonstrated it with a particular example from a hot-arid climate. A theoretical comparison between traditional and modern urban forms revealed the sometimes counter-intuitive yet beneficial characteristics of the courtyard typology.

Knowles [33] introduced the solar envelope as a method to optimise building form for receiving solar rays and limiting shading by neighbouring buildings. This solar envelope is a three-dimensional surface, on a given site, that does not obstruct more than n hours of sun onto adjacent sites [30,70,71,77,92,93]. This idea was later extended by Capeluto and Shaviv [93], who distinguished between solar rights envelopes and solar collection envelopes. The maximum height buildings can have before they cast shadows on neighbouring buildings during a certain time of the year is the Solar Rights Envelope. The lowest possible position windows and passive solar collectors on buildings can have before they get shaded by neighbouring buildings during a certain period in winter is the Solar Collection Envelope. The volume that exists between both envelopes is called the Solar Volume (SV).

5. Ventilation in urban blocks

Air flow around buildings has a direct effect on the indoor and outdoor thermal comfort and air quality and on the energy use of buildings.

Prediction of airflow and ventilation can be affected by several factors. Some of the factors relate to the climate and weather which include wind speed and wind direction. One of the most essential sources of power for indoor natural ventilation is the wind pressure difference over the building and pressure fluctuations on the facade. This pressure difference can help the air to come inside and move through the building. The arrangement of adjacent buildings in relation to wind direction strongly influences natural ventilation [94,95].

Other factors which affect ventilation relating to the urban layout are topography, street depth and neighbourhood layout. Investigating the air flow inside an urban canyon is a big topic which can be divided into several scales. Studies which investigate air flow patterns on an urban scale are categorised into four dimensional ranges: regional (up to 100 or 200 km), city (up to 10 or 20 km), neighbourhood (up to 1 or 2 km), and street scale (less than 100–200 m) [96]. Factors that relate to the building design are the facade, the size and location of openings, the geometry and orientation of the building [94,97,98].

This review paper will focused on neighbourhood scale only. The main reason to study neighbourhood scale is to know more about the flow within the urban canyon. The wind flow, particularly within the canyon, may also be changing as it moves from one neighbourhood to the next.

5.1. Effect of urban block form on ventilation

Concentrating on the air flow inside a building without investigating the effect of the adjacent neighbourhood on the wind pressure coefficient on the building's facade cannot be helpful to better understand the whole process of natural ventilation [95].

When considering air flow and ventilation disperse on the scale of streets, the geometry of canyons (height-to-width ratio) is the main factor [85,99]. In deep street canyons, variations in wind speed can be important leading to significant temperature differences over the street canyon (approximately 5 °C). This temperature difference may have a great impact on the heating and cooling loads of buildings [100]. Johansson [101] compared a deep canyon ($H/W=9.7$) to a shallower one ($H/W=0.6$). He showed that during the day the deep canyon was colder than the shallower one. For this reason, in summer the deeper canyon had a more favourable temperature than in winter. In contrast, the shallower canyon was more favourable in winter since it permitted more solar access [101].

Besides the height-to-width ratio, the building arrangement is one of the important parameters for improved wind flow and should be considered by city planners and architects. Zhang et al. [95] evaluated the effects of three different building arrangements on wind pattern. They found that for natural ventilation the wind environment of two improved arrangements with lower interval-to-height ratio was better than that of the reference layout with higher aspect ratio. The numerical results also showed that changing the wind direction from perpendicular to the facades to 45° incidence has significant effect on the flow field (Fig. 6).

The orientation of buildings in relation to prevailing wind direction is another factor that affects urban block ventilation. Jóźwiak et al. [102] experimented to study the influence of wind direction on natural ventilation. The tests were carried out on models of an apartment building complex consisting of six adjacent buildings. They indicated the necessity of not only modelling the boundary layer but also the close surroundings of a building. They concluded that there are significant differences in pressure distributions with and without modelling the boundary layer and the neighbourhood (Fig. 7).

Tsutsumi et al. [37] modelled some blocks in order to find out the wind pressure on groups of buildings. The relations between the

average wind pressure coefficient in a model and various layouts of the buildings are mainly discussed. Wirén [103] investigated pressure distributions on a Swedish single-family building surrounded by identical buildings in various arrays. He concluded that the density of the surrounding buildings affects the distribution and the magnitude of the wind pressure on the test building surface.

Furthermore, Bady et al. [94,104] used a wind tunnel to investigate the indoor natural ventilation in terms of wind pressures on the surfaces of cubic buildings of a street located within a high density urban area. Four typical models with different geometries were examined for different wind directions. They measured the wind pressure coefficient on the surfaces of the buildings. The study results proved that the configuration of buildings and the wind direction are very important factors that determine the induced natural ventilation within urban domains since they characteristically influence the flow yielding differences in wind pressure.

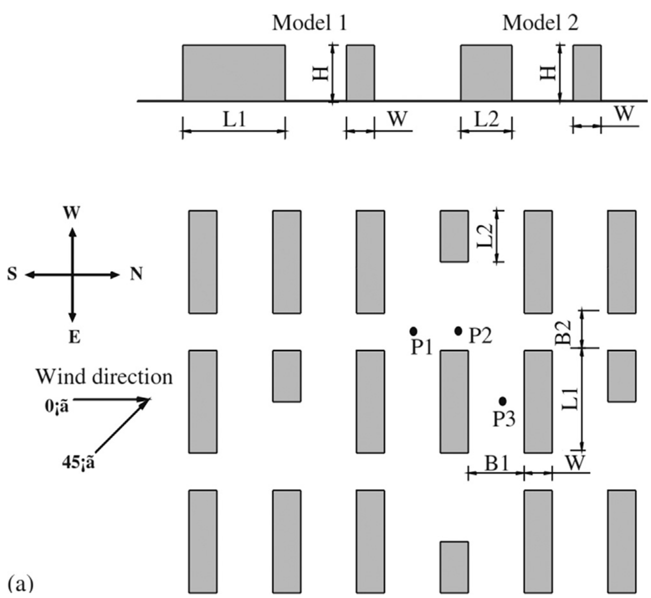

Fig. 6. The ratios examined by Zhang et al. [96].

Thapar and Yannas [105] investigated the impact of ventilation and vegetation in providing a comfortable microclimate of urban square in hot and humid climate.

In all the literature reviewed, the wind pressure on and wind pressure coefficient of the facade of buildings were studied. The main purpose is to understand the effect of surrounding buildings on the potential of air flow inside the building. It seems that studies that research the influence of neighbourhood layout on wind pressure (coefficients) and at the same time study air flow patterns inside buildings are very limited.

5.2. Ventilation analysis techniques and methods

There are three common techniques to predict and study wind flow

- field measurements,
- laboratory-scale physical modelling (wind tunnel),
- computational fluid dynamics (CFD) [106].

Traditionally, the analysis and evaluation of the wind environment mainly depended on wind tunnel tests. Wind tunnel studies of pedestrian-level wind conditions focus on determining the mean wind speed and turbulence intensity at pedestrian height (full scale height 1.75 or 2 m). Wind tunnel tests are generally point measurements with Laser Doppler Anemometry (LDA) or Hot Wire Anemometry (HWA) [6].

Nowadays, numerical simulation (often called computational fluid dynamics, CFD) has been widely accepted owing to the tremendous progress of computer capabilities in recent years, and the advances in numerical modelling. Especially, if optimisation design is to be undertaken and the environmental impact of planned urban developments is to be assessed, the numerical modelling is preferred to wind tunnel experiments, as the tests are usually expensive and laborious particularly in the case of additional test requirements with modified building and environmental configurations. In the recent past, many numerical simulations concerning urban wind fields have been carried out. Johnson and Hunter [107] performed numerical studies on urban canyons using

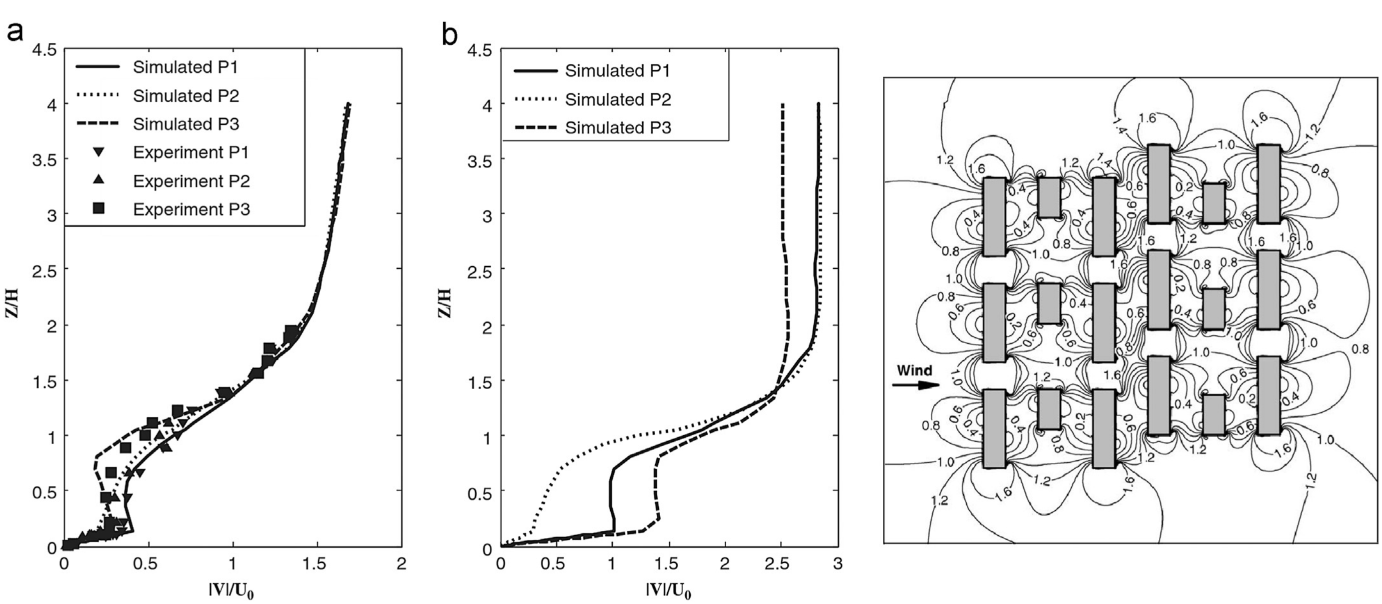

Fig. 7. Experimental and numerical normalised wind velocity: (a) S–N wind and (b) computed normalised velocity field at 2 m from the ground level for S–N wind direction [96].

the $k-e$ turbulence model and made a preliminary comparison of wind tunnel results with numerical models He and Song [108] used large eddy simulation (LES) approach to compute and evaluate the pedestrian wind environment under different geometry and wind conditions. They concluded that the numerical model was accurate by comparing numerical results with a number of standard wind tunnel tests. Their conclusion showed that the two methods had general agreement but that the numerical simulation overestimated the concentration gradient within the canyon air space. He et al. [97] simulated the air flow distributions in a built-up area with regularly aligned blocks, and examined the possibility of practical use of cyclic boundary conditions. Due to the complexity of the problem, the general rules are hard to be established and specific studies are needed for different building designs.

Zhang et al. [95] compared computational results with experimental data for vertical velocity profiles (Fig. 6). They concluded that computational results are generally in good agreement with the experimental data for the locations experimentally tested. The results also showed that the numerical method is a more economical and faster tool to evaluate the wind environment.

6. Conclusion

This paper reviewed studies that considered energy performance of buildings in their city context. All reviewed studies in this paper try to investigate the energy use of the building not as an individual block but in a group of buildings. For this purpose, all studies were categorised into three main groups. Studies that

1. Investigated the effect of urban block geometry on the thermal behaviour inside and outside the building.
2. focused on issues of solar access inside and outside the building for passive heating and daylighting purposes.
3. Evaluated the effect of urban block form on indoor and outdoor ventilation.

Furthermore, indicators and methods in each group of studies were discussed.

This paper showed that it is difficult to study the impact of the neighbourhood on thermal behaviour of a building because it is hard to describe all relevant indicators simultaneously. As a result, there are limitations in the methods and techniques that describe the energy performance of buildings in relation to their surrounding micro-climate.

Finally, most of the works in this field focused on solar radiation because it is the most important parameter and there are more methods to estimate the solar potential on an urban scale. From this literature review, it seems that studies that research the influence of neighbourhood layout on wind pressure (coefficients) and at the same time study air flow patterns inside buildings are very limited.

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